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TARGETED ENERGY TRANSFER PHENOMENA FROM PRIMARY STRUCTURES TO GEOMETRICALLY NONLINEAR LIGHTWEIGHT ATTACHMENTS: AN OVERVIEW

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1 INTRODUCTION

We present an overview of targeted energy transfer (TET) phenomena, whereby broadband vibration energy of primary structures gets passively directed to and dissipated by local lightweight, geometrically nonlinear attachments [1-5]. The local attachments possess essential nonlinearities, e.g., they lack linear components; as a result, they have the capacity to affect the global dynamics of the primary systems to which they are attached, through series of transient or permanent resonance captures occurring at arbitrary frequency ranges. Moreover resonance capture cascades, e.g., TET from multiple modes are possible.

2 TARGETED ENERGY TRANSFERS DUE TO ISOLATED RESONANCE CAPTURES OR RESONANCE CAPTURE CASCADES

The term *Targeted Energy Transfer – TET* is used here to refer to the one-way (on the average) transfer of vibration energy from a structural component to a predetermined spatial area (a nonlinear energy sink – NES) where the vibration localizes and is passively dissipated. The NES possesses essentially nonlinear (e.g., nonlinearizble) stiffness nonlinearities, and does not possess a preferential resonance frequency. Hence, depending on its instantaneous energy, the NES is capable of resonantly interacting with structural modes at arbitrary frequency ranges. This resonance interaction is either with a single structural mode (isolated resonance capture), or with a series of modes (resonance capture cascades). It follows that the NES acts, in essence as passive, broadband, adaptive boundary controller.

We can demonstrate nonlinear TET by considering a linear (main) structure with (N+1) degrees-of-freedom (DOF) that is weakly coupled to a local essentially nonlinear attachment at point O [6]. The attachment consists of a nonlinearizable stiffness nonlinearity of the third order in parallel with a viscous dashpot that models energy dissipation; throughout this work the mass of the NES will be taken m=1. The coupling stiffness between the linear and nonlinear parts is assumed to be linear and weak, of order ε, $0 < \varepsilon << 1$. In addition, the connection between the two systems is assumed to be one-dimensional.

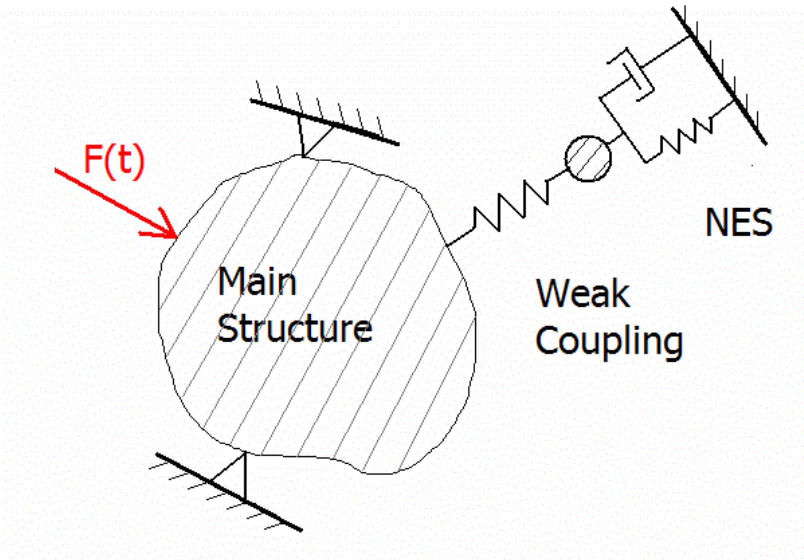
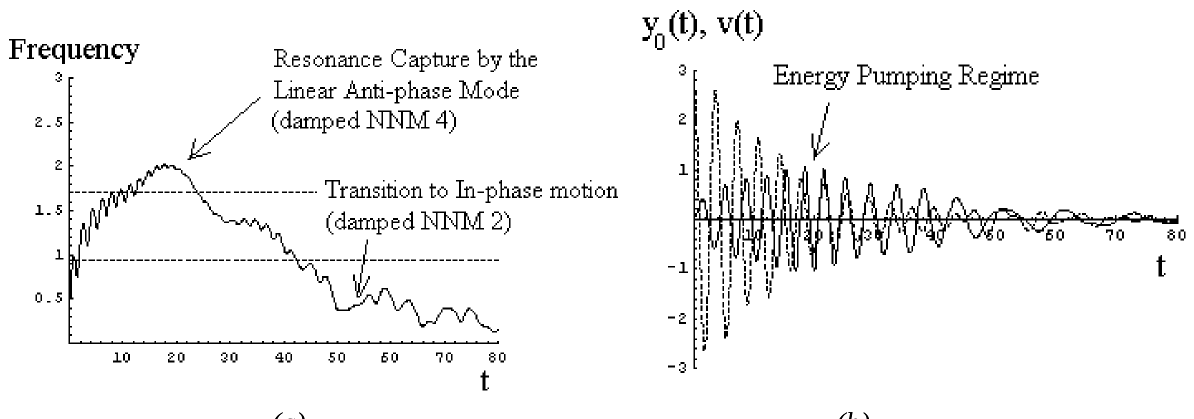


Figure 1: Main System - NES Configuration

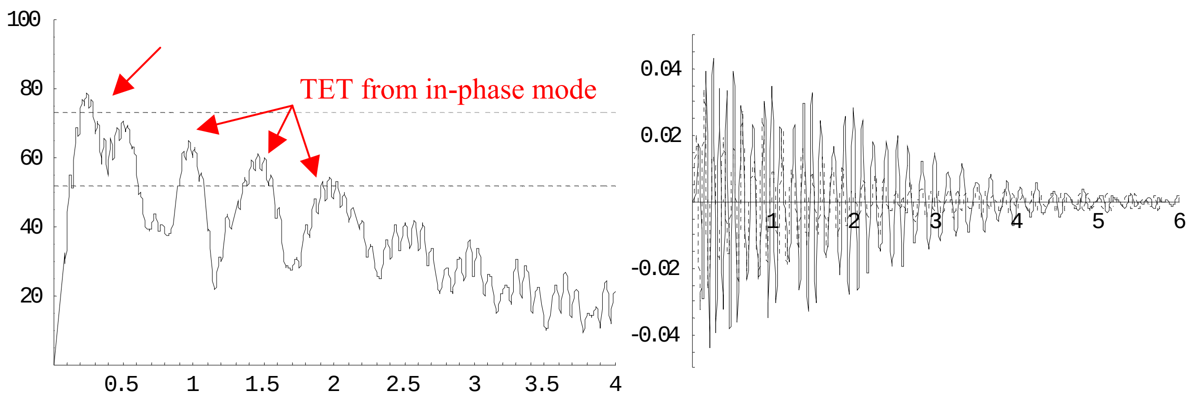
TET from the linear subsystem to the nonlinear oscillator occurs under the condition of 1:1 resonance capture whereby the nonlinear oscillator resonates transiently with a mode of the linear subsystem, and energy is transferred (pumped) to the nonlinear attachment in a one-way, irreversible fashion. In that case the nonlinear attachment acts, in essence, as a nonlinear energy sink (NES). We note that due to its essential nonlinearity, the NES lacks a 'preferential' resonance frequency and, as a result, can resonate with any of the (N+1) modes of the linear structure, depending on the instantaneous energy of the vibration (cf. Figure 2 for an isolated resonance capture corresponding to impulsive excitation of a two-mode structure [6]). Moreover, cascades of resonance captures are possible, wherein the NES resonates with a sequence of modes, extracting from each mode a certain amount of energy before proceeding to the next. Resonance capture cascading is caused by energy dissipation in the system, which with increasing time (and decreasing overall energy) induces resonances of the NES with modes of the linear subsystem at monotonically decreasing frequencies (cf. Figure 3 for a resonance capture cascade of an impulsively forced two mode structure [6]).



(a) *(b)*

Figure 2. Isolated resonance capture: (a) Instantaneous frequency of the NES; (b) Response of point of attachment of the structure ------ and of NES ——.

TET from out-of-phase mode



(a) *(b)*

Figure 3. Resonance capture cascading: (a) Instantaneous frequency of the NES, with the levels corresponding to the two eigenfrequencies of the linear subsystem indicated by dashed lines; (b) Response of point of attachment of the structure ------ and of NES ——.

Damping is a prerequisite for TET. Moreover, the paradoxical fact is that the energy dependence of the free synchronous periodic solutions [nonlinear normal modes (NNMs)][7] of the undamped, unforced system governs, in essence, the energy pumping properties of the corresponding damped and forced system. This is because resonance capture in the damped system amounts, in essence, to excitation of a damped NNM invariant manifold that for O(ε) weak damping is $\varepsilon-\tilde{}$close to the corresponding NNM of the undamped system (the damped NNM manifold can be regarded as an analytic continuation of the corresponding NNM of the underlying undamped system). It follows that the energy dependence of the damped NNM invariant manifold (where the motion takes place) governs the dynamics of the energy pumping process. Moreover, by properly designing the NNMs of the undamped system one should be able to enhance the energy pumping process in the *damped* system.

Since the essential cubic nonlinearity plays an important role for the realization of TET, special care was given for its construction. Essential (nonlinearizable) cubic nonlinearity can be realized by different structural configurations through geometric nonlinearities. In a particular experimental fixture we considered the configuration of Figure 4 consisting of a thin rod (piano wire) with no preload clamped at both its ends, performing transverse vibrations at its center. Then, the geometric nonlinearity induced by the deformation of the wire generates the essential nonlinearity required for the TET phenomenon. In Figure 8 we present a typical experimental TET result for an impulsively loaded single-degree-of-freedom system coupled to an NES [8].

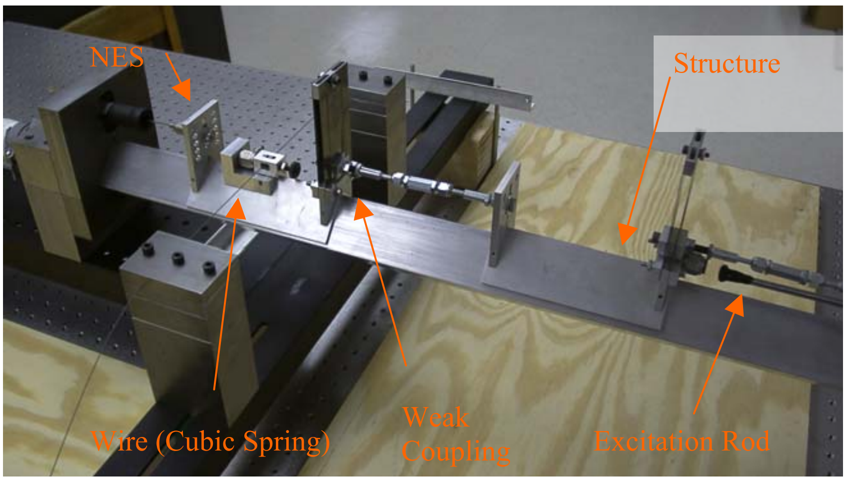


Figure 4: Experimental fixture for the TET study [8].

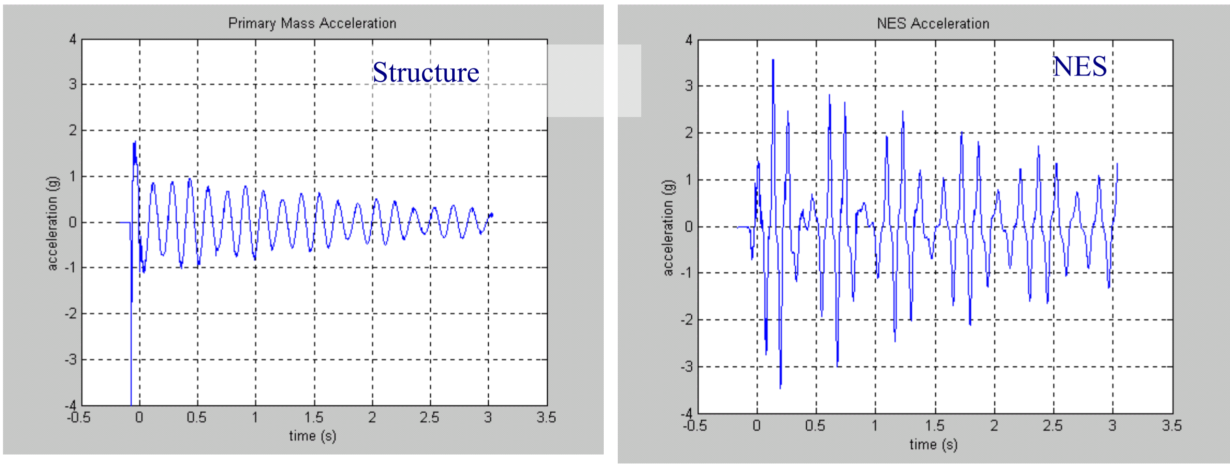


Figure 5. Experimental TET.

3 CONCLUSIONS

Essentially nonlinear attachments due to geometric nonlinearities can induce TET phenomena in coupled oscillators. Applications of TET can range from shock isolation [1,2] and aeroelastic instability suppression [3], to drill-string dynamics [4] and seismic mitigation [5]. Current work focuses on theoretical and experimental development of the concepts of TET and NES.

REFERENCES

[1] S. Tsakirtzis, *Passive Targeted Energy Transfers from Elastic Continua to Essentially Nonlinear Attachments for Suppressing Dynamical Disturbances*. PhD Thesis, National Technical University of Athens, 2006.

[2] F. Georgiades, *Nonlinear Localization and Targeted Energy Transfer Phenomena in Vibrating Systems with Smooth and Non-smooth Stiffness Nonlinearities.* PhD Thesis, National Technical University of Athens, 2006.

[3] Y.S. Lee, *Passive Broadband Targeted Energy Transfers and Control of Self-Excited Vibrations*. PhD Thesis, University of Illinois, 2006.

[4] V. Regis, *Passive Vibration Mitigation in Rotor Systems Using Nonlinear Energy Sinks*. MSc Thesis, University of Liege, 2006.

[5] F. Nucera, *Nonlinear Energy Pumping as a Strategy for Seismic Protection*, Fransesco Nucera. PhD Thesis, University of Calabria at Arcavacata of Rende – Cosenza, 2005.

[6] *Dynamics of Linear Discrete Systems Connected to Local Essentially Nonlinear Attachments* 2003. A.F. Vakakis, L.I. Manevitch, O. Gendelman, L.A. Bergman. Journal of Sound and Vibration, Vol. 264, pp. 559-577.

[7] *Normal Modes and Localization in Nonlinear Systems*, A.F. Vakakis, L.I. Manevitch, Y.V. Mikhlin, V.N. Pilipchuk, A.A. Zevin. ISBN: 0471133191, John Wiley & Sons, May 1996.

[8] *Experimental Study of Nonlinear Energy Pumping Occurring at a Single Fast Frequency* 2005, D.M. McFarland, L.A. Bergman, A.F. Vakakis. International Journal of Non-Linear Mechanics, Vol. 40, pp. 891-899.